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SPACE STORABLE HYBRID ROCKET TECHNOLOGY DEVELOPMENT

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Hybrid rocket propulsion is gaining a great deal of interest for space storable and low temperature applications. Typical hybrid propellants have been shown to survive over a wide range of temperatures, minimizing the need for thermal control. This ability to survive in low temperature environments, coupled with their high performance (comparable to liquid bipropellants) and ability to restart has made them viable candidates for a variety of missions. A technology development program at the Jet Propulsion Laboratory over the last three years has focused on increasing the Technology Readiness Level (TRL) of hybrid rockets for a potential Mars Ascent Vehicle (MAV), In Situ Resource Utilization (ISRU) and Interplanetary SmallSat applications. Results of this technology development will be presented.

INTRODUCTION

Hybrid rockets show a great deal of promise for space storable and low temperature applications. A technology development program has been ongoing at the Jet Propulsion Laboratory (JPL) to increase the TRL of a hybrid propulsion system for use in low and variable temperatures like those present on Mars. Testing from small scale (~3-inch diameter) to a full-scale prototype Mars Ascent Vehicle (MAV) (~11-inch diameter as currently envisioned) has been completed at two subcontractors. A new fuel, called SP7, was specifically formulated for this application. It is a wax-based fuel with increased strength properties and temperature range as compared to paraffin, which is a common, high-regression rate hybrid fuel. In order to determine the capabilities of the newly developed fuel, material testing and thermal cycling of the fuel grains was completed at JPL and NASA Marshall Space Flight Center (MSFC) respectively. A parallel task to identify and test solid additives that are hypergolic (combust on contact) with the oxidizer has identified several options and has now completed a successful ignition. Additionally, efforts to miniaturize the technology to enable interplanetary SmallSats will be discussed.

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HYBRID PROPULSION

Hybrid rockets typically utilize a solid fuel and liquid or gaseous oxidizer. Figure 1 highlights the liquid oxidizer and solid fuel on the 2016 Point of Departure Review concept for a hybrid MAV.[1] The liquid oxidizer is introduced into the combustion chamber, where the fuel grain is housed. An igniter initiates combustion by vaporizing some fuel and add heat to the system. Alternatively, and as will be described in a following section, a material that is hypergolic with the oxidizer can be added to the fuel. Oxidizer contacting the fuel/additive mixture would then ignite on contact and this reaction is used to vaporize fuel and initiate combustion. The current MAV concept does not take credit for this, but its future inclusion is promising.

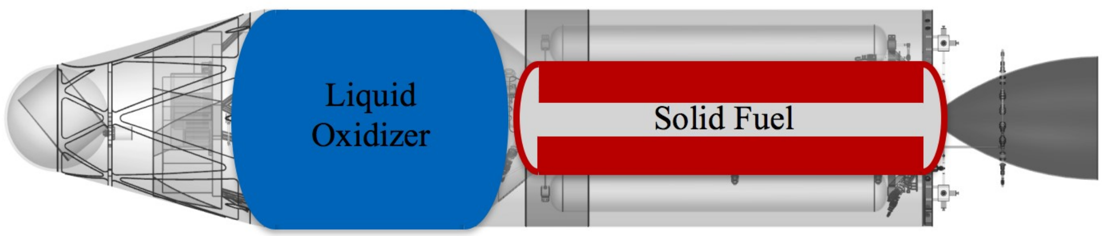

Figure 1. A hybrid MAV concept with the propellants highlighted.

High regression rate hybrid fuels (such as waxes) have led to a resurgence of interest in the technology. These fuels form a liquid layer on the surface of the grain as they burn. Oxidizer flowing over the fuel grain produces a shear force that entrains droplets into the flow, essentially acting as a fuel injection system for the motor. Combustion of classical hybrid fuels relies on a diffusion limited heat transfer mechanism, which limits how quickly it burns, and therefore the amount of thrust the rocket can produce. In the past, methods for increasing the available surface area for burning, such as adding additional ports, have been investigated. However, these solutions were found to have substantial drawbacks for large scale applications. However, classical fuels are finding their place in small to moderate size applications, such as the CubeSats that will be discussed near the end of this paper.

A HYBRID MARS ASCENT VEHICLE

Five major periods of work on a potential Mars Ascent Vehicle have been undertaken in the past 20 years.[2] This paper focuses on the results of the most recent period, which began in 2014 and is ongoing. This was when a study at JPL reopened consideration of all types of propulsion systems. Ten potential options for a Mars Ascent Vehicle (MAV) were evaluated as part of this study in 2014.[3] The most promising options based on that initial study were evaluated in detail the following year (2015). These included: two-stage solids, Single Stage to Orbit (SSTO) pumped and regulated bipropellants, and a SSTO hybrid.

The projected payload mass for these designs grew in between the initial evaluation and the more detailed study, resulting in an increased mass for each of the systems. However, throughout these iterations, the hybrid remained the lowest Gross Lift Off Mass (GLOM) option. The added promise of its low temperature capability, minimizing the need for thermal control and therefore minimizing system mass, made this low TRL option highly desirable. With support from the Mars Program Office, focus shifted in 2016 to the design and technology development for a hybrid MAV. The hybrid concept was frozen after a 2016 Point of Departure Review (PoDR) and has been used for development in FY17 through the present.[1]

The hybrid design uses a new propellant combination capable of low-temperature storage and operation: wax-based, solid fuel (SP7) and mixed oxides of nitrogen (MON30) for the oxidizer. MON30 is 70% N_2O_4 and 30% NO and has a depressed freezing point compared to neat N_2O_4. Concentrations of NO from MON3 to MON25 are/have been used for different Earth-based rocket applications. Concentrations higher than MON25 are not required for Earth-based applications. This particular concentration leads to an Allowable Flight Temperature (AFT) of lower than -70 C based on a freezing point of MON30 at around -80 C[4].

The low TRL aspects of this propulsion system lead to the need for technology development. Earth ambient testing of a similar combination: SP7 with MON3, is currently being conducted at Whittinghill Aerospace and SPG. Thermal cycling and material property tests of the new fuel have been conducted showing the capability of the fuel. A procedure for processing the full-scale fuel grains has been established at MSFC. Finally, solid hypergolic additives have been discovered for use with MON. Each of these advancements will be discussed in the next sections.

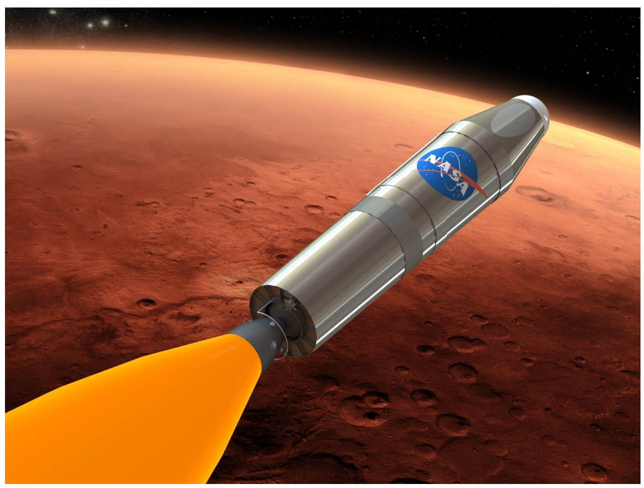

Figure 2. Artist's conception of a hybrid MAV during launch

TECHNOLOGY DEVELOPMENT FOR A POTENTIAL MARS ASCENT VEHICLE

New fuel formulation

SPG developed a new solid fuel formulation for this application.[5] It has to survive over a wide temperature range (50 C to -100 C desired), have lower thrust than paraffin with comparable performance, and enable the inclusion of solid additives. The performance of the newly developed wax-based fuel, SP7, is very similar to paraffin. Its specific impulse is within approximately 1 second of paraffin with MON3.

It was predicted that the new formulation would have a lower regression rate than paraffin, which translates to lower thrust. This was desired in order to minimize the RCS usage after the first burn. The regression rate of SP7/N_2O was determined to be between 60 and 70% that of SP1x, SPG's standard, paraffin-based hybrid fuel. The regression rate coefficients are: 7.81×10^{-5}

and n = 0.545. Later testing at small scale with MON (discussed in the next subsection) followed the same trend. The final regression rate correlation is still being determined through the large-scale testing.

Fuel Processing

SP7 was specifically formulated to be slower burning than paraffin. This enables lower thrust throughout the burn and gives the design an advantage as it transitions to RCS control after the first burn. SP7, however, has a higher viscosity when melted and this more viscous fuel was harder to cast into fuel grains than initially expected. Paraffin is typically spun cast. The wax is melted and introduced into some sort of containment cylinder (often an insulator) that is allowed to cool while spinning. This makes a simple, smooth, cylindrical port down the center of the fuel grain. The material properties of SP7 are not conducive to spin casting. Therefore, MSFC investigated ways to make the fuel grain in segments, working their way up to a monolithic fuel grain. The fuel grains were cast without a center bore and then machined to the required dimensions.

Subscale Testing

Testing in FY2016 was done at a small scale (2.7-inch motor) to determine the regression rate of the propellant combination given above. Initial tests were completed at SPG with N_2O as the oxidizer, because of its relative safety and ease of use (the subcontractor already had the facilities/feed system set up for testing with N_2O). It was expected that the regression rate curves would be very similar between the N_2O and N_2O_4, which turned out to be true. Eight tests of the SP7/MON3 combination were completed and verified that the regression rate followed a comparable curve to the ~30 tests of SP7/N_2O.[54]

Several of the tests chilled the fuel and oxidizer to -60 C prior to testing. However, the fuel was allowed to warm up before the test could be completed. The cold grains (typically about -20 C at the time of test) did not show noticeably different regression behavior. This environmental testing will have to be conducted at larger scale, however, these initial successes gave confidence in the approach being pursued.

Full Scale Testing

Full scale (~11-inch diameter fuel grain) testing is currently being completed at two subcontractors: Space Propulsion Group and Whittinghill Aerospace. Each subcontractor designed their own motor for these tests and each has the goals of achieving high combustion efficiency (>95%, c* efficiency), stability (+/- 5% peak to peak variability in chamber pressure), liquid injection thrust vector control (LITVC), an autonomous restart and a full duration burn. This round of tests is expected to wrap up this spring. This specific propellant combination turned out to be harder to ignite and maintain stable combustion than anticipated. However, both subcontractors have had successful tests at the 11-inch scale and are taking different approaches to meet these goals.

A hotfire test of Whittinghill Aerospace's 11-inch motor is shown in Figure 3. Plumbing directing MON-3 to the two LITVC valves in the nozzle is clearly visible at the aft end of the motor. Multiple tests have confirmed the LITVC capability. Data from these tests is being used to determine how much MON needs to be injected to obtain desired deflections. Original predictions were made using data from previous tests conducted at Whittinghill (with other oxidizers), data available in literature and a Computational Fluid Dynamics model.

A hotfire test at Space Propulsion Group's facility in Butte, MT is shown in Figure 4. SPG has been challenged with some Mars-like temperature conditions as they continue their testing this winter.

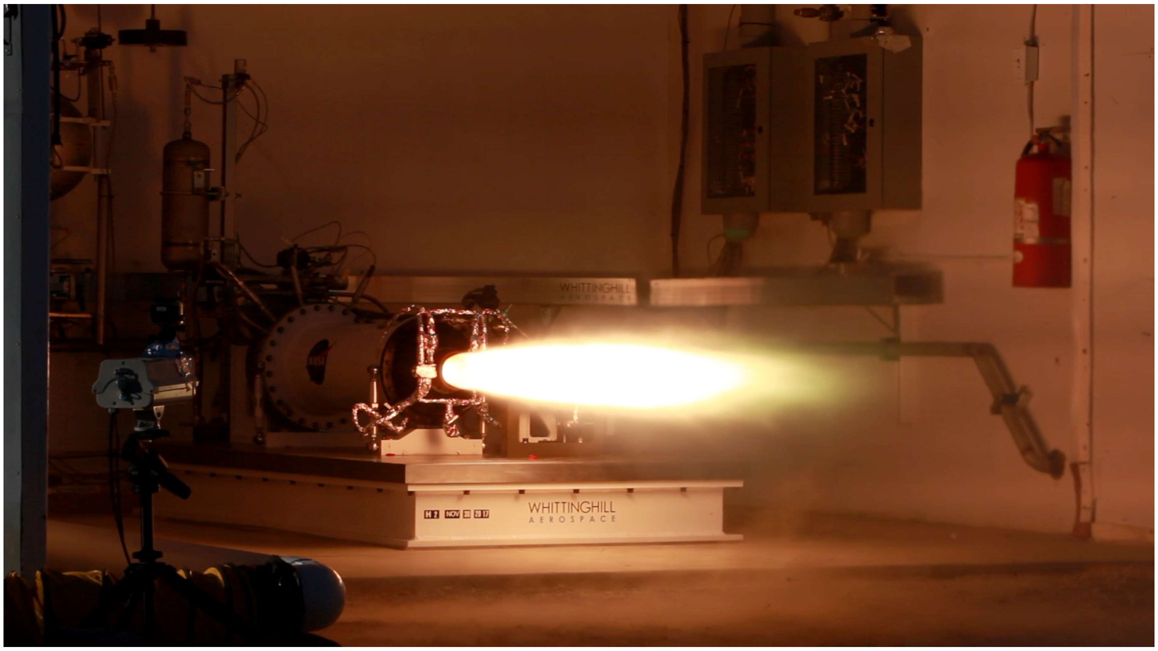

Figure 3. Still image from a 60-second test at Whittinghill Aerospace.

Figure 4. Still image from a 20-second test at Space Propulsion Group.

Hypergolic Ignition Testing

Testing has been carried out at Pennsylvania State University[6] and Purdue University[7] to determine suitable solid additives to the fuel grain which could be used to hypergolically start the motor. Each university researched potential options and selected candidate materials. Purdue and Penn State identified several good candidates through a preliminary screening process. This process included drop testing, which basically consisted of dropping MON oxidizer onto small amounts of each candidate materials. The best additives were Sodium Amide (Penn State's top candidate) and Potassium bis(trimethylsilyl) amide (PBTSA, Purdue's top candidate). Purdue has been evaluating these top two candidate materials in their 2-inch rocket test facility within Zucrow Laboratories. They have successfully achieved hypergolic ignition using MON3/SP7 with Sodium Amide. They attempted and achieved three starts on the same motor. This is a dramatic step forward in reducing the complexity of multiple start hybrids. A still image from this successful test is included in Figure 5. Tests with PBTSA will be conducted shortly.

Figure 5. Still image from a hypergolic ignition test of MON3/SP7 & Sodium Amide at Purdue University.

Future Work and Remaining Challenges

A substantial amount of work is still be required to advance hybrid motors to the point at which they could be incorporated into a potential Mars Sample Return mission. The motors need to be qualified under flight environments. Vacuum testing at Mars ambient conditions could be used to achieve this. While the propellants themselves can survive over the wide range of temperatures expected on Mars, the mismatch in coefficients of thermal expansion will need to be carefully examined as flight-like designs mature. This is expected to be the biggest challenge in the design, since the fuel is typically surrounded by both an insulator and combustion chamber structure and each material will likely expand/contract differently under temperature changes.

The results of the hypergolic ignition testing have been very promising. Therefore, the processing of full scale fuel grains with these additives needs to be investigated.

SMALLSAT TECHNOLOGY DEVELOPMENT

Classical hybrid fuels are finding a niche in small satellites. The lower regression rate fuels are ideal for the modest thrust required for controllability of these low mass spacecraft during maneuvers. Since these typically fly as rideshare payloads, the enhanced safety of the inert hybrid propellants makes them even more attractive. A detailed systems trade comparing hybrid propulsion to a liquid monopropellant option has been completed and shows their promise.[8] Since the time of the study, a different propellant combination, Polymethyl methacrylate (PMMA aka acrylic) and gaseous oxygen, has been selected due to its commercial availability and combustion stability. Finally, a flight design for a Mars reference mission concept, including orbit insertion after a rideshare to Mars and multiple flybys of Phobos and Deimos has been completed.[9]

PMMA and O_2 are being tested at JPL for these SmallSat applications. Long-duration burns (95 s) have been demonstrated, showing capability to complete large ΔV maneuvers, such as orbit insertion. Figure 6 shows a still from this long duration test of the heavy weight motor. For trajectory correction maneuvers and orbit maintenance, multiple shorter burns will be required, so multiple ignitions (up to five so far) have been demonstrated, again with a heavy weight motor in the JPL test facility. A more flight-like motor is currently being fabricated and will be tested in rough vacuum this summer, raising the TRL to 5. A candidate control system based on PID state feedback has been designed to control the spacecraft during motor operation. This control system leverages six cold gas thrusters to maintain sub-degree pointing accuracy throughout the burn and six low output cold gas thrusters for attitude control during the science phase of the mission. The cold gas thrusters for both the thrust vector control system and the attitude control system make use of the gaseous oxygen oxidizer, thereby minimizing the associated dry mass of the complete propulsion system.

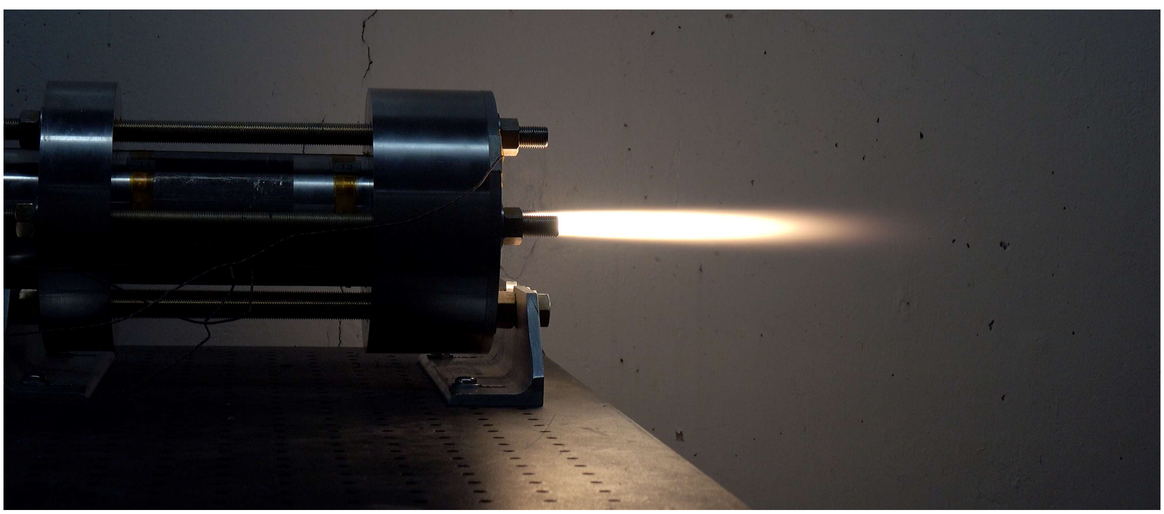

Figure 6. Still image from the 95-second test of the PMMA/GOx motor at JPL.

Hybrid motors for SmallSats are being investigated at other institutions. For example, NASA Ames is testing acrylic and N_2O[10] and Utah State University is looking at 3D-printed Acrylonitrile butadiene styrene (ABS),[11] among others. Their high performance, commercial availability and inherent safety make hybrids attractive candidates for SmallSat missions.

Test Results

More than 50 tests have been completed to investigate propellant combinations for SmallSat motors. The selected propellant combination has had 32 tests completed to date, including nine tests of over 60 seconds and five sequential, autonomous ignitions.

OTHER APPLICATIONS

A previous study at JPL has investigated hybrid rockets for in situ resource utilization. As the size of the rocket grows, this becomes more attractive, especially on Mars with the potential to convert CO_2 into liquid oxygen. A short study was conducted in 2014 to evaluate a hybrid MAV for a robotic sample return mission. However, the power story did not close at that time. As new batteries become available, it would be interesting to evaluate this option again. Hotfire testing of paraffin wax fuel grains with an oxidizer made up of O_2 with varying concentrations of CO_2 was completed to determine the purity requirements that would be imposed on the conversion of CO_2 to O_2.

Hybrid rockets could be useful for outer planet orbit insertion. Typically, these missions use a substantial percentage of the spacecraft power to keep the propellant(s) above their freezing points. The low temperature development currently being investigated for use on the Mars surface could have direct applicability to this application as well.

CONCLUSION

Hybrid rocket propulsion is a promising candidate for space storable applications. Advantages associated with this propulsion technology are leading to investments in its development within NASA. These benefits include high performance, tailorable thrust profiles (through fuel selection) and low temperature survivability. Large-scale testing is currently being completed to mature a wax-based fuel/MON propellant combination for a potential Mars Ascent Vehicle. No show stoppers have been identified and the testing continues to yield improvements in performance and stability. Hybrid motors using classical (slow burning) fuels are being considered for SmallSat propulsion. The high specific impulse and relatively high thrust enables large ΔV maneuvers such as orbit insertions. The non-toxic propellant combination PMMA/gaseous O_2 is being tested for this application at JPL.

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